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# AUTOMATE: A RESEARCH PARADIGM TO STUDY COLLABORATION IN MULTIDISCIPLINARY DESIGN TEAMS (U)


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**FOR THE COMMANDER**

Kenneth R Boff

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The purpose of this report was to describe the development of a research paradigm to study multidisciplinary design teams. An historical overview of multidisciplinary design teams identified two issues critical for effective collaboration: information sharing and avoidance of misanalogies. The process of developing a research paradigm to focus on these issues involved finding a design problem and eliciting knowledge from design experts. The problem selected was the design of an automobile navigation system (AutoMate). To identify key tradeoffs to build the task around, knowledge was elicited from 13 design experts. The design experts were interviewed and their knowledge concept mapped. Based on the design experts' knowledge, the AutoMate task was developed. The task and its potential uses are discussed.



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## TABLE OF CONTENTS

LIST OF FIGURES . . . . . vi

LIST OF TABLES . . . . . vii

INTRODUCTION . . . . . 1

BACKGROUND AND HISTORICAL OVERVIEW . . . . . 1
Collaboration in Multidisciplinary Design . . . . . 2
Critical Issues in Collaboration . . . . . 3

FINDING A DESIGN PROBLEM . . . . . 5

ACQUIRING KNOWLEDGE ABOUT THE DESIGN OF

AN AUTOMOBILE NAVIGATION SYSTEM . . . . . 14
Method . . . . . 14
Subjects . . . . . 14
Procedure . . . . . 14
Results . . . . . 15
Process Issues . . . . . 15
Team Composition . . . . . 15
Timeline Phases . . . . . 17
Tradeoff Issues . . . . . 17
Display Hardware . . . . . 23
Display Type . . . . . 23
Color Versus Monochrome Screen . . . . . 23
Control Issues . . . . . 24
Display Format . . . . . 25
Track-Up Versus North-Up Map Orientation . . . . . 25
Menus . . . . . 25
Variable Zoom Issues . . . . . 25
Visual Versus Auditory Displays . . . . . 26
Navigation Systems . . . . . 27
GPS vs. INS . . . . . 27
Context . . . . . 28
Weather Issues . . . . . 28
Safety Issues . . . . . 29
Glare Issues . . . . . 29
Traffic Issues . . . . . 29

DESCRIPTION OF THE EXPERIMENTAL TASK: AUTOMATE . . . . . 30

POTENTIAL APPLICATIONS FOR AUTOMATE . . . . . 32

REFERENCES . . . . . 33

APPENDIX A. Sound Board Options . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 36

APPENDIX B. Design Specifications For The Automate Audio Display . . . . . . . . . . . . . 37

APPENDIX C. Speech Synthesis Options . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 38

APPENDIX D. Human Factors Information . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 39

APPENDIX E. Computer Engineer Information . . . . . . . . . . . . . . . . . . . . . . . . . . . . 40

APPENDIX F. System/Safety Engineer Information . . . . . . . . . . . . . . . . . . . . . . . . . 41

LIST OF FIGURES

Figure 1. Concept Interpreter Matrix . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 16

LIST OF TABLES

Table 1. List and Description of Design Problems . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 7

Table 2. Tradeoff Issues and Sub-Issues with respect to Discipline Perspective . . . . . . . . . . . 18

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## INTRODUCTION

The purpose of this project was to design an experimental paradigm to study collaboration in multidisciplinary design teams. According to Bulkeley (1993), the number of organizations using the multidisciplinary design team approach is increasing. For most designers, the major drawbacks of multidisciplinary design teams revolve around communications with other team members (Bulkeley, 1993). Designers feel that too much time must be devoted to design team meetings. Preparation for meetings and the actual time spent in these meetings reduces the amount of time designers have to work on the design itself. Simply scheduling meetings may be time consuming. If team members are not located in close proximity (i.e., in the same building, city, state, etc.), travel time needs to be factored in. In addition, understanding and keeping track of input from all team members can be overwhelming.

To alleviate some of these problems, computer and information technologies are being used more and more for communication and team decision support. Bulkeley (1993) noted that designers rated computer tools that supported design and communication among their most important design tools. These tools include such things as group decision support systems, groupware products, electronic mail (email), computer conferencing, design rationale databases, etc. The impact these technologies have on the process of design team collaboration and decision making are still relatively unknown. Furthermore, because many of these technologies are still being developed, we felt that research on design team collaboration could potentially inform their development. As an initial first step in a program of research focused on computer support for team design, we developed an experimental paradigm to study the process of collaboration in design teams. The focus of this paper is on the development of this paradigm.

This paper begins by describing the background and gives an historical overview of multidisciplinary design. Critical issues for effective collaboration are highlighted. Next, the steps taken to develop an experimental task for multidisciplinary design teams are described. Included is a discussion of the selection of a design problem and the elicitation of knowledge from design experts. The paradigm and its rationale are then described. Finally, the potential uses for the paradigm are discussed.

## BACKGROUND AND HISTORICAL OVERVIEW

Redesigns and long product life cycles can be very costly in product design. According to Kochan (1991), United States and European designers spend, on average, 50% of their time in redesign activities. In contrast, their Japanese counterparts spend only 10% of their time on redesign. Similarly, the typical product development lead time in Europe is 63 months, as compared to 43 months in Japan. Multidisciplinary design (also known as concurrent engineering) has been suggested as a way to get products to market quicker with fewer costly redesigns (Kochan, 1991; Sobieski, 1990).

This approach involves designers from various specialties (e.g., industrial engineering, mechanical engineering, human factors, production manufacturing) working together to integrate knowledge early in the design process. Concurrent engineering shortens the product life cycle (i.e., the time it takes for product development from inception to market) because tasks can be done simultaneously. Fewer redesigns are necessary because designs are scrutinized from multiple viewpoints prior to fixing or constraining the design.

In contrast, more traditional approaches generally involve design tasks being completed sequentially and independently. Kochan (1991) refers to this as "over-the-fence" engineering. Once a group of designers from a particular discipline completes their contribution to the design,

they pass it on to the next department or group of designers. By designing sequentially, the problem is viewed from a single, narrow perspective at each step of the way. Designers who are involved early have greater control over the final outcome. Designers who get involved later simply fulfill a design evaluation role. They are limited to making recommendations for design changes.

Unfortunately, at this point, there may be a reluctance to make the recommended modifications or changes. Redesigning may be costly. Furthermore, the goals of designers in the early stages may be categorically different from those involved in later stages. Early on the goal may be to design something that works. Later in the process the goal may become one of designing something that can be manufactured cheaply and efficiently, as well as something that will be user friendly. Often times these goals are incompatible. In addition, when components are designed independently, the parts may not be integrated easily.

The concurrent engineering approach is believed to be an improvement over traditional approaches because it: shortens product development cycles, results in designs that are simpler and cheaper to manufacture, results in better designs, improves quality and reliability, produces products that match customer's needs more precisely, results in better cost controls, helps the organization be more competitive, and reduces the need for changes late in the design process (Bulkeley, 1993; Kochan, 1991).

## Collaboration in Multidisciplinary Design

As the popularity of the concurrent engineering approach and multidisciplinary design grows, the need for better understanding of collaboration among design team members is needed. According to Gray (1989), collaboration involves interdependent stakeholders with different perspectives who have joint ownership and collective responsibility for decisions and who must work together constructively to arrive at solutions.

Because multidisciplinary design involves collaboration among a variety of team members, it may be best understood as situated problem solving. This perspective posits that problem solving takes place within a particular context (i.e., the situated context) and that this context shapes how the problem is approached and solved. A situated context is one that involves social interdependence between actors who share responsibility for solving the problem. Through social interaction, the individuals construct a joint understanding of the problem, develop shared values and norms, and become involved in a reciprocal exchange of knowledge (Lave, 1991). In this sense, the situated context is not static, but always evolving and changing as the problem and its solution unfold.

According to Young and McNeese (in press), there are 10 factors that characterize situated problem solving. First, solving the problem must require the use of multiple cognitive processes and multiple paths to the solution. Second, the context in which the problem occurs is complex and provides a wide array of perceptual cues that inform those involved about the possibilities that the situation affords. Third, solving the problem involves identifying attributes of the problem and separating the irrelevant from the relevant information. Fourth, several competing solutions can be generated for the problem. Fifth, given the uncertainty involved in solving the problem and its ill-structured nature, the problem is best approached by generating sub-problems. Sixth, the context is interpersonal and involves social interaction. This social interaction defines the roles of the actors and the meaning of their actions. Seventh, as the group works out the problem, they build a shared perception or understanding of the problem and its potential solutions. Eighth, situated problem solving involves the integration of distributed knowledge. Distributed knowledge means that each individual brings to the situation unique information based on past experiences and learning

opportunities. Across the group, this information may reflect a variety of domains and specialties. The group must then share and integrate each member's unique information. Ninth, as the problem unfolds, the group establishes a pattern of interaction. This pattern or developmental history becomes part of the context and heavily influences later interactions and decisions. Finally, in situated problem solving, the context involves values, intentions, and goals that have personal and social significance. Thus, the situated context has important implications for individuals' identities.

Multidisciplinary design is similar to situated problem solving because it can be characterized as "a goal oriented, constrained, decision-making exploration, and learning activity that operates within a context that depends on the designer's perception of the context" (Gero, 1990, p. 28). The design develops through the social interaction of the team members. Because they come from a variety of disciplines, knowledge is distributed across team members. Members of the team work on the design task relying on their own unique information and other team members to educate them.

Critical Issues in Collaboration

Unfortunately, multidisciplinary design teams do not effectively share distributed knowledge. Research on group decision making (Stasser, 1992; Stasser & Titus, 1985; 1987) has shown that groups tend to focus their discussion on commonly shared information and neglect to discuss unique or unshared information. This results in groups arriving at incorrect or faulty decisions. Because only one member of the team knows a particular piece of information, it has a lower probability of being brought up in group discussions.

Team members may also have difficulty sharing information because they do not share a common framework. Often individuals from different disciplines misunderstand and misinterpret what each other says. Because of differences in their backgrounds and training, they speak different languages (Boff, 1987). Each discipline has its own jargon, metaphors, acronyms, definitions for words, labels etc. (Bucciarelli, 1988). In some instances, the same label may be used to explain exact opposite things (Fotta & Daley, in press). Without a common framework, the advantages of the multidisciplinary team approach cannot be realized.

Although a multidisciplinary team may share a common goal, team members may identify more strongly with their own discipline than with the team as a whole. Bucciarelli (1988, p. 168) observed that "decisions made across disciplines are best seen as negotiations among parties who, while sharing a common goal at some level, hold different interests." If communication is difficult, both a shared perception and a shared identity may be more difficult to build.

Furthermore, designers draw heavily on their previous design experience. So instead of generating and carefully evaluating all possible design alternatives, designers rely on a case-based design strategy (Gero, 1990; Klein, 1987). In case-based design, designers draw analogies between their present design and previous ones. Case-based designs are efficient because features of a previous design can be incorporated into the new design project. Unfortunately, unnecessary components of the original design may also get incorporated. Because these features are spuriously associated with essential ones, they needlessly restrict the design options considered. Designers may have trouble differentiating and articulating which features are essential and which are not. The result may be misanalogies. Misanalogies occur when previous learning is applied to a situation where it may be inappropriate or conflict with other aspects of the design. Because misanalogies are difficult to articulate, they add to the communication problems multidisciplinary design teams face.

Coordinating communication may be difficult for multidisciplinary design team members because they may work on different schedules or may be separated by physical distances. For example, anyone who has played telephone tag, understands the frustration that can result from being unable to communicate with another team member. Add to this time constraints and you have a potentially volatile situation. The result may be that team members fail to communicate with one another and base decisions on incomplete or inaccurate information.

As noted earlier, organizations are using multidisciplinary design teams to develop high quality new products, quickly and efficiently. Effective collaboration is important to successfully implement this approach. Thus, understanding the nature of the collaboration process and how computer tools (e.g., groupware, email) can aid collaboration is necessary. We focused our attention on developing an experimental paradigm because of the difficulty in assessing the effectiveness of design decisions and errors in a naturalistic environment. Furthermore, we were interested in examining cause and effect relationships between computer support for multidisciplinary design and effective collaboration. In addition we felt an experimental paradigm would allow for comparisons between different computer tools to support collaboration. The next two sections describe the development of the research paradigm focusing on two key steps: finding a design problem and eliciting knowledge from designers.

## FINDING A DESIGN PROBLEM

Designing a research paradigm to study collaborative design issues involved finding a design problem that could be developed or adapted into an experimental task. A literature review was conducted to find a design problem that could be adapted for use in our research paradigm. Engineering, design, and human factors journals were extensively surveyed, as well as the *Science and Technology Index*. In addition, we conducted computerized searches of the PSYCHLit and ERIC databases.

To be considered as a task candidate, design problems were judged in relation to five criteria established prior to our literature review. The first criterion was that the task had to be based on a "real world" design problem. This "real world" perspective was driven by the desire to produce an experimental context that was relevant and meaningful for design teams to participate in. Also, this would enable research to be undertaken in both field and laboratory settings. In addition, a "real world" based task would increase the external validity of the task enhancing the generalizability of future research.

The second criterion was that the problem had to be multidisciplinary in nature. This meant that the design problem had to involve consideration of various disciplines. Therefore, it had to be sufficiently complex so that knowledge from more than one discipline would be necessary to complete the design. The disciplines that might be involved in such a design would be management, marketing, engineering (i.e., electrical, computer, human factors, industrial, etc.), psychology (i.e., experimental, social, human factors, etc).

Third, the problem had to incorporate or include consideration of human factors issues (e.g., display design issues, human-computer interaction issues, mental workload issues, ergonomics issues, anthropometry issues, etc). This criterion was included because of its relevance to the overall purpose of our research team. Our research team was interested in how human factors information gets incorporated into collaborative design projects. We hoped this knowledge would ultimately contribute to the development of groupware products that facilitate the retrieval and incorporation of human factors information and expertise into the design process.

Fourth, we wanted a design problem that had the potential to be completed both in an individual and team context. The task had to involve information from a variety of perspectives such that a team could work on it without perceiving the task as trivial. At the same time, the task had to have the potential to be accomplished by a single individual. This would provide flexibility in designing future experiments (e.g., multiple levels of analysis).

Fifth, design professionals, as well as, university students must be able to complete the problem. This meant that the problem should be relevant and meaningful to a student, as well as interesting and engaging for design professionals. Ideally, the problem would have characteristics that were familiar to both university students and professional designers.

Forty-one design problems were selected for consideration using these criteria (See Table 1). The majority of these design problems had been used as instructional projects in college level design and engineering courses. Some were actual on-going design projects.

From these problems we selected the task of designing a navigation display for an automobile (Dingus, 1990). This design problem satisfied all of the pre-established criteria. First, designing a navigation system for an automobile was a real design project. Several systems have

been designed and some are currently being tested. Second, this design problem required the input of many disciplines (e.g., engineering, psychology, hardware, software, etc.). Third, human factors issues (e.g., human-computer interaction issues, display design issues, etc.) were taken into consideration in previous design endeavors of automobile navigation systems. Fourth, we felt that the design could be completed by both individuals and teams of designers. Fifth, the design problem focused on a system to aid individuals in driving and navigating an automobile. Because these behaviors are likely to be familiar to both designers and students, we felt that it had the potential to be an interesting and engaging experimental task for both groups.

Table 1. List and description of design problems.

| Problem | Description | HFIssues | Considerations | Teams |
|---|---|---|---|---|
| **Moving Map Naviga-tion System**<br><br>(Dingus, 1990) | -automobile navigation interface<br>-dual task consisting of visual and control components | -control theory<br>-visual display<br>-workload<br>-attentional demands<br>-HCI<br>-Dual task | -time (2-3 weeks)<br>-initial member competitiveness<br>-groupthink type of phenomenon | Yes<br><br>3 per team |
| **Easy-Banker**<br><br>(Ballay, 1987) | -payment of credit card bills by modem hookup to the bank<br>-consisted of cardreader, keypad, lcd display, voice recognition cell<br>-design observed in traditional and CAD environment | -ergonomic issues<br>-HCI<br>-visual display<br>-manual control | Must meet requirements:<br>1) HF and Usability<br>2) functional specifications<br>3) budget & quality<br>4) physical form<br>5) graphic presentation (marketing) | No |
| **Wheel-chair Lap Tray**<br><br>(Miller & Hyman, 1989) | -lap tray for a speech generating communication device<br>-designed for woman with CP and only head control | -ergonomic issues<br>-ease of use<br>-safety<br>-usability<br>-size | -Must meet all HF requirements<br>-approved by rehabilitation staff & faculty<br>-economical | Yes<br><br>less than 5 |
| **Foot Pedal Commu-nication System**<br><br>(Miller & Hyman, 1989) | -communication device for CP woman with no control<br>-Foot pedal communication device was developed to alert others | -ergonomic issues<br>-reliability<br>-safety<br>-size<br>-ease of use | -Must meet all HF requirements<br>-approved by rehabilitation staff & faculty<br>-economical | Yes<br><br>less than 5 |
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| **Motorized Wheel-chair Simulator**<br><br>(Miller & Hyman, 1989) | -designed a motorized simulator for joystick training for young children who will need wheelchairs later in life | -ergonomic issues<br>-reliability<br>-safety<br>-size<br>-training usefulness | -Must meet all HF requirements<br>-approved by rehabilitation staff & faculty<br>-economical | Yes<br><br>less than 5 |
| **Chemical Process Plant**<br><br>(Moray, 1989) | -Engineering and Psychology students collaborated to design a chemical process plant<br>-Instructor tried to provide "realism" through letters from CEO of Chemical Co etc. | -signal detection<br>-control theory<br>-task analysis<br>-workload<br>-visual display selection<br>-auditory display selection<br>-safety | -competitiveness among members<br>-time<br>-efficient | yes<br><br>size not stated |
| **Durian Opener**<br><br>(Ling, 1988) | -design for opening a Durian (thick-skinned) tropical fruit<br>-design based on pulling, twisting, and pressing | -ergonomic issues<br>-ease of use<br>-safety | -time<br>-materials (less metal the better)<br>-economic | yes,<br><br>6 or more |
| **Board-game**<br><br>(Fai, 1989) | -one student developed and built a 3-d boardgame<br>-interdisciplinary aspect:<br>1) industrial design<br>2) engineering design<br>3) manufacturing engineer<br>4) marketing | -color<br>-attention<br>-ergonomic issues | -limited expertise outside their own field<br>-time | No |
| **Work-Station: Mobile Ground Shelter**<br><br>(Frey, 1990) | -design of a mobile ground shelter<br>-used an iterative process of CAD and foam "life size" mock-ups(4) to design MGS | -habitability<br>-operational utility<br>-workspace design<br>-visual display selection<br>-auditory display selection | -Access to users. | Yes,<br><br>size not stated |
| **Commer-cial Airline Dis-patcher**<br><br>(e-mail) | -Design of a dispatcher's workstation<br>-student project | -HCI<br>-visual displays<br>-cooperative problem-solving<br>-auditory displays | | yes |
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| **Personnel Database**<br><br>(e-mail) | -Modeling of contaminated site to develop on-base personnel database<br>-the information provided (money, manpower, and time) was used to base decisions on direction of cleanup effort<br>-collaboration of environmental engineer & computer scientist<br>-on-going "real" project | -information management<br>-HCI | | yes |
| **Program-mable Thermo-stat**<br><br>(e-mail) | -programmable thermostat for zoned home heating system<br>-multi-disciplinary approach including: heating-ventilation, air-conditioning engineers, industrial/product designers, electrical/electronic engineers, HCI designers, and marketing<br>-Project for HCI students | -HCI issues | -not very constrained<br>-faked a lot of information | yes |
| **Distance Education**<br><br>(e-mail) | -design of a program of "long distance" education (or remote education)<br>-course in finance<br>-team effort consisting of manager, SME, editor, visual designer, and instructional designer at a minimum | -visual presentation<br>-computer-mediated communication<br>-learning<br>-training | -time<br>-distance<br>-technology | yes |
| **Precision Train Assembly**<br><br>(Busch-mann &Weib-mantel, 1990) | -evaluation of an assembly process for a 180 part model train<br>-used "ease of assembly" rules for evaluation of assembly process | -safety issues<br>-manipulability of parts | -Possible social loafing | yes,<br><br>5 per group |
| **Deepsea Salvage**<br><br>(Kantowitz, Sorkin, Shively, & Payne, 1983) | -reliability of sonar, detection, & location of vessel<br>-project to demonstrate calculating reliability in serial and parallel systems<br>-recalculation methods after adding or removing components | -HCI<br>-visual display<br>-auditory display.<br>-reliability | | |
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| **Emer-gency Vehicle**<br><br>(Kantowitz, et al, 1983) | -design of an auditory alarm to indicate vehicle in reverse (VIR) | -auditory display<br>-visual display<br>-auditory localization<br>-attention<br>-workload | | |
| **Controls**<br><br>(Kantowitz, et al, 1983) | -redesign of control panel to improve accessibility as measured by "index of accessibility" | -ergonomic issues<br>-control layout | | |
| **Data Entry**<br><br>(Kantowitz, et al, 1983) | -design or selection of a data entry device | -HCI<br>-visual display<br>-training<br>-attention<br>-workload | -cost<br>-software available | |
| **Floor Plans**<br><br>(Kantowitz, et al, 1983) | -evaluation of house floor plans | -physical layout<br>-functionality<br>-usability | -cost<br>-architectural<br>-aesthetics | |
| **Airport Terminal**<br><br>(Kantowitz, et al, 1983) | -design of airport terminal | -physical layout<br>-workspace design<br>-safety | -cost<br>-aesthetics | |
| **Multi-functional Remote Controller**<br><br>(Tang, 1991) | -design of a unified remote control that controls 3 devices from three specified categories (e.g. stereo receiver, TV, VCR) | -visual display<br>-HCI issues<br>-control issues<br>-ergonomic issues | -all participants were Mechanical Engineering graduate students<br>-students had never collaborated together before | yes, 3 or 4 per, 2 teams |
| **Laser Printer**<br><br>(Dingus, 1990) | -redesign of a laser printer interface<br>-develop a usability test plan<br>-redesign included controls, display, menus, messages, and documentation | -visual display selection<br>-auditory display selection<br>-HCI issues<br>-physical layout | -time (2-3 weeks)<br>-initial member competitiveness<br>-groupthink type of phenomenon | yes,<br><br>3 per team |
| **Ground Trans-porter Cab Controls**<br><br>(Dingus, 1990) | -design of cab controls for large ground transporter<br>-develop test plan<br>-construct mock-ups<br>-make simulation recommendations | -control theory & layout<br>-ergonomic issues<br>-visual display selection<br>-workload<br>-attentional demands | -time (2-3 weeks)<br>-initial member competitiveness<br>-groupthink type of phenomenon | yes,<br><br>3 per team |

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|---|---|---|---|---|
| **Text Editor** (Dingus, 1990) | -design of a simple software application for use by novices<br>-develop usability test<br>-determine alternate designs | -HCI issues<br>-visual display | -time (2-3 weeks)<br>-initial member competitiveness<br>-groupthink type of phenomenon | yes,<br>3 per team |
| **Grocery Stand** (Dingus, 1990) | -redesign of a grocery store checkout stand | -ergonomic issues<br>-efficiency<br>-performance | -time (2-3 weeks)<br>-initial member competitiveness<br>-groupthink type of phenomenon | yes,<br>3 per team |
| **Clinical Labs** (Sanders & McCormick 1982) | -design information flow and network in labs<br>-analyze the information receiving, information storage, information processing, and decision making, as well as the action functions of the lab. | -information processing<br>-performance<br>-decision making<br>-Information management<br>-task analysis<br>-safety issues<br>-reliability issues | -quick turn around time on specimen (time)<br>-accurate results<br>-correct interpretation of results | |
| **Metal Ingots** (Sanders & McCormick 1982) | -in fictitious manufacturing plant calculate the work pace and cost of lifting in terms of energy expended<br>-workers lift metal ingots for storage | -safety<br>-performance<br>-work pace<br>-efficient<br>-physical workload demands | -cost | |
| **Stalk Controls** (Sanders & McCormick 1982) | -redesign of stalk controls<br>-stalk controls are mounted on the steering wheel of your car and usually have multiple controls (i.e. cruise control, turn signals, etc.) | -control theory<br>-ergonomic issues<br>-usability<br>-functionality<br>-mental workload<br>-reliability | -cost | |
| **Soldering Iron** (Sanders & McCormick, 1982) | -redesign of soldering iron because of high accident rate<br>-application of principles of practical tool design | -tool design<br>-ergonomic issues<br>-safety | -cost | |
| **Wheel-barrow** (Ledsome, 1987) | -Design of a garden wheelbarrow | -ergonomic issues<br>-safety | -cost<br>-materials<br>-marketing considerations | |
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| **Note-Cards Recep-tionist (NC-Recep)**<br><br>(Tang, 1989) | -redesign of a hypertext software system (NoteCards) to manage and redirect phone messages | -HCI | -1 hour for discussion<br>-1 group had limited programming experience<br>-members had never collaborated together before | yes, 3 per team, 2 teams |
| **Macintosh Visualiza-tion (MacViz)**<br><br>(Tang, 1989) | -design of the integration of Mac PC's into a course called Visual Thinking | -learning<br>-HCI | -1 hour for discussion<br>-1st and 2nd team consisted of essentially the same members<br>-most members had collaborated together before | yes, 3 or 4 per team, 2 teams |
| **Custom-ized Phone (Custom-Phone)**<br><br>(Tang, 1989) | -design of a multiple function telephone (e.g. answering machine, call waiting, forwarding, conferencing)<br>-Human Factors students participated | -auditory display<br>-visual display<br>-HCI<br>-reliability | -students had never collaborated together before | yes, 3 per team, 2 teams |
| **Silk Swirl**<br><br>(Droz, 1991) | -Design of a portable device that washes, rinses, and drys delicate apparel<br>-graduate & undergraduates participated<br>-simultaneous multidisciplinary approach to design | -reliability<br>-ergonomic issues | -teams consisted of 2 persons from 3 different disciplines | yes, 6 per team |
| **Child Finder**<br><br>(Droz, 1991) | -design of a device that located wandering children<br>-graduate & undergraduates participated<br>-simultaneous multidisciplinary approach to design | -visual display<br>-auditory display<br>-attention<br>-safety<br>-HCI | -teams consisted of 2 persons from 3 different disciplines | yes, 6 per team |
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| **Go-Punch**<br><br>(Droz, 1991) | -design of a portable hole-punch<br>-graduate & undergraduates participated<br>-simultaneous multidisciplinary approach to design | -ergonomic issues | -teams consisted of 2 persons from 3 different disciplines | yes, 6 per team |
| **Kwik Kool**<br><br>(Droz, 1991) | -design of a device that cooled a beverage in 45 seconds without diluting it<br>-provided working prototype<br>-simultaneous multidisciplinary approach to design | | -strict deadline of 1 semester | |
| **EasyOut**<br><br>(Droz, 1991) | -design of a door knob that was easier for senior citizens and handicapped people to use<br>-simultaneous multidisciplinary approach to design | -safety<br>-ergonomic issues | -strict deadline of 1 semester | |
| **Wrinkle Away**<br><br>(Droz, 1991) | -design of a portable hand-held fabric steamer<br>-simultaneous multidisciplinary approach to design | -ergonomic issues<br>-safety | -strict deadline of 1 semester | |
| **Snuggler**<br><br>(Droz, 1991) | -design of a terry cloth garment/towel to aid adults when giving baths to infants<br>-simultaneous multidisciplinary approach to design | | -strict deadline of 1 semester | |
| **Dyna Bounce**<br><br>(Droz, 1991) | -design of new athletic footwear using borosilene<br>-simultaneous multidisciplinary approach to design | -ergonomic issues | -graduate & undergraduates participated<br>-teams consisted of 2 persons from 3 different disciplines | yes, 6 per team |

Note. "Ergonomic issues" refers to the physical and physiological requirements/constraints of the human in human-machine design.

# ACQUIRING KNOWLEDGE ABOUT THE DESIGN OF AN AUTOMOBILE NAVIGATION SYSTEM

Once a design problem had been chosen, the second phase of task development began. The second phase involved acquiring knowledge or information about the issues involved in designing a navigation system for an automobile. In particular, we focused on potential tradeoffs involved in designing within a multidisciplinary team context. The method and results of this knowledge acquisition are described in detail below.

## Method

### Subjects

Thirteen design professionals were interviewed and concept mapping was used to represent their information. The design professionals included human factors psychologists and engineers, a software specialist, a display hardware specialist, an electrical engineer, and an industrial engineer.

### Procedure

An interactive interview format was used to elicit knowledge from subject matter experts (in this case design experts) about our design problem. Concept Mapping (McNeese, Zaff, Peio, Snyder, Duncan, & McFarren, 1990; Novak & Gowin, 1984) was used to represent this knowledge. Concept maps are graphical networks of concept nodes and links. Concept nodes represent actions, events, or objects and are connected by various relational links. These relational links convey information about the interconnection between two concept nodes and usually are prepositions or verbs (McNeese, et al., 1990). We focused on the concept-relation-concept unit (i.e., a concept "triplet") as our primary unit of examination.

Sessions were conducted in a conference room that had been modified for the purpose of these interviews and concept mapping. The room contained several whiteboards fastened to the walls. A Macintosh computer was located on a conference table in the center of the room. The Macintosh was used to input a computerized version of each expert's map for later analysis. The application program used for this purpose was called the Concept Interpreter and was developed at Armstrong Laboratories to facilitate the recording and analysis of concept maps (Snyder, et al., 1991). In addition, sessions were audio taped for later review and analysis.

Involved in each concept mapping session was a design expert, an interviewer, and an additional panel of researchers associated with the project. The interviewer converted the knowledge elicited from the expert into a concept map. The additional panel of researchers served to elicit additional information from the expert as needed. The panel used probe questions to clarify or expand existing concepts.

At the onset of the concept mapping session, experts were seated at a conference table. The concept mapper began by giving a brief introduction to concept mapping and described the purpose of the interview. This included conveying information concerning our goal to construct a research paradigm. At this point, the concept mapping interview started.

During the concept mapping sessions, the information relayed by the expert was drawn onto the whiteboards so that the expert and the interviewer could view it simultaneously. The

expert was encouraged to interact with the concept map by suggesting changes and additions. Also, the expert was encouraged to elaborate on information already represented in the map to clarify any "fuzzy" areas. Each concept mapping session took approximately one to three hours.

The rationale behind using this format was threefold. First, the concept map served as an external memory aid indicating to the expert what has been discussed and stimulating the recall of additional information (McNeese, et al., 1990). Any misunderstandings or misinterpretations that the interviewer had could be corrected "on-line" by the expert. Second, the external representation of knowledge was available to the expert to help organize the information that had been communicated. Third, concept mapping allowed the interviewer to locate and identify central issues and concepts nodes within a given subject area. The interviewer could prompt the expert for additional information pertaining to these issues. Usually, as design experts interacted with the concept maps more, the quality and quantity of the elicited information increased.

## Results

The concept interpreter matrix is presented in Figure 1. The matrix indicates the number of concepts and links in each map. The number of concepts discussed by each expert ranged from 77 to 191. The number of triplets (i.e., links) ranged from 79 to 207. The matrix also indicates whether reference to a particular category appeared in each of the 13 concept maps. A dot indicates that an element of that category was mentioned once. A circle and a dot indicate that two or more elements from that category were discussed. As can be seen from Figure 1, there was a good deal of consistency across the experts. The experts covered many of the same issues. The next section summarizes the key issues identified by the experts.

To facilitate the discussion, the categories from the concept interpreter were broken down into two groupings: process issues and tradeoff issues. Process issues focused on identifying team members (i.e., who is on the team), the timeline of a "typical" design, and the objective or design mission. Tradeoff issues focused primarily on the types of constraints and tradeoffs different team members might face in designing an automobile navigation system. Both types of information were useful for building the task. The process information helped to specify what types of disciplines (e.g., software engineers, marketing analyst, program manager) should be represented in the research paradigm, the steps involved in designing a navigation system for an automobile, and what was a reasonable task for designers to do in a limited amount of time. The tradeoff issues helped identify the structure of the task and provide "real world" information for creating the task materials. Each grouping will be discussed in more detail below.

### Process Issues

*Team Composition.* Six disciplines were mentioned consistently across the maps. Over half of the experts who discussed team composition indicated these disciplines. The prototypical design team included: 1) a human factors psychologist / engineer, 2) a hardware / display engineer, 3) a software engineer / programmer, 4) a manager, 5) a marketing analyst / user representative, and 6) a system / safety specialist.

| Concept Map | Team | Timeline | Objective | Constraints | General Hardware Issues | Software Constraints | HF Constraints | Marketing | Users | Managing | Format of Display | Error Management | Context | Display Hardware | Navigation System | Computer System | Control Hardware | Car/System Interface | Maintainability | UNDEFINED |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Design Expert 1 (163 nodes / 176 links) | ◉ | ◉ | ◉ | ◉ | ◉ | ■ | ◉ | ◉ | ◉ | ◉ | ◉ | ◉ | | ◉ | ■ | ◉ | ◉ | ◉ | ◉ | ◉ |
| Design Expert 2 (150 nodes / 160 links) | ◉ | ◉ | ◉ | ◉ | ◉ | ◉ | ◉ | ◉ | ◉ | ◉ | ◉ | ◉ | ◉ | ◉ | ◉ | ◉ | ◉ | ◉ | ◉ | ◉ |
| Design Expert 3 (191 nodes / 207 links) | ◉ | ◉ | ◉ | ◉ | ◉ | ◉ | ◉ | ◉ | ◉ | ◉ | ◉ | ◉ | | ◉ | | | | | | ◉ |
| Design Expert 4 (97 nodes / 115 links) | ◉ | ◉ | ◉ | ◉ | ◉ | ◉ | ◉ | ◉ | ◉ | ◉ | ◉ | ◉ | | ◉ | ◉ | | ◉ | ◉ | | ◉ |
| Design Expert 5 (120 nodes / 138 links) | ◉ | ◉ | ◉ | ◉ | ◉ | ◉ | ◉ | | | ◉ | ◉ | ◉ | | ◉ | | | ◉ | ◉ | | ◉ |
| Design Expert 6 (109 nodes / 121 links) | ◉ | ◉ | ■ | ◉ | ◉ | ◉ | ◉ | ◉ | ◉ | ◉ | ◉ | ■ | | | | | | | ■ | ◉ |
| Design Expert 7 (97 nodes / 107 links) | ◉ | | ◉ | ◉ | ◉ | ◉ | ◉ | | ◉ | ◉ | ◉ | ◉ | | ◉ | ◉ | ◉ | ◉ | ◉ | ◉ | ◉ |
| Design Expert 8 (165 nodes / 176 links) | ◉ | | ◉ | ◉ | ◉ | ◉ | ◉ | ◉ | ◉ | ◉ | ◉ | ◉ | ◉ | ◉ | ◉ | ◉ | ◉ | ◉ | ■ | ◉ |
| Design Expert 9 (118 nodes / 128 links) | ■ | | | ◉ | ■ | ◉ | ◉ | | ■ | ◉ | ◉ | ◉ | | ◉ | ◉ | ◉ | ◉ | ◉ | ◉ | ◉ |
| Design Expert 10 (130 nodes / 147 links) | ◉ | ◉ | ◉ | ◉ | ■ | ◉ | ◉ | | ◉ | ■ | ◉ | ◉ | ■ | ◉ | ◉ | ◉ | ◉ | ◉ | | ◉ |
| Design Expert 11 (147 nodes / 169 links) | ◉ | | ◉ | ◉ | ◉ | ◉ | ◉ | ◉ | ◉ | ■ | ◉ | ◉ | | ◉ | ◉ | ◉ | ◉ | ◉ | | ◉ |
| Design Expert 12 (77 nodes / 79 links) | ■ | | | ◉ | ■ | ◉ | ◉ | | ■ | ◉ | ◉ | ◉ | ◉ | ◉ | | | ◉ | ◉ | | ◉ |
| Design Expert 13 (130 nodes / 146 links) | ◉ | | | ◉ | ◉ | ◉ | ◉ | | ◉ | ◉ | ◉ | ■ | ◉ | ◉ | | ◉ | ■ | ◉ | ◉ | ◉ |

Figure 1: Concept Interpreter Matrix

*Timeline Phases.* Four phases were discernible from the matrix results. The steps identified by the experts were: 1) marketing definition phase, 2) team assembly phase, 3) developmental planning phase, 4) full scale development and prototyping phase, and 5) implementation phase. According to the experts, the marketing definition phase would involve the identification of a niche or marketing need for the product. This would include conducting a small feasibility study to assess whether the product could be produced profitably. In the second phase, team members would be identified and assigned responsibilities. Typically the team members would represent the disciplines discussed above. During the developmental planning phase, the team would stipulate the specifications and performance requirements for the product. The full scale development phase would be an iterative process that involves prototyping, identifying problems, correcting problems, and refining the design. This would be the phase where most design tradeoffs and bottlenecks would become apparent. During this phase, beta versions of the product would be created, tested, and evaluated. The final phase, implementation, would involve releasing the final product.

## Tradeoff Issues

This section discusses design tradeoffs identified by the experts. For the purposes of this paper, tradeoffs were defined as issues where two or more disciplines were needed to provide information for final design decisions. Design tradeoffs could be issues where the needs or constraints of one discipline override the needs or constraints of another, or just where input is needed from multiple disciplines. Owing to the complexity of relationships among disciplines, issues, and tradeoffs, we have organized the material and our description according to the schema of Table 2. Four major categories of design tradeoffs were identified by the Experts: a) Display Hardware, b) Display Format, c) Navigation System, and d) Context. Each of these categories contained major issues (indicated by upper-case letters in Table 2) and each of these major issues had subissues (indicated by lower-case letters in Table 2). These issues and subissues are listed in the leftmost column of Table 2. The middle columns indicate the disciplines identified as part of the design process. Disciplines concerned with tradeoffs for an issue or subissue are darkened (within a row) to indicate a common concern or interest. The row beside major issues (upper-case letters) indicate the overall level of interaction between the various disciplines. The rows beside the subissues (lower-case letters) indicate the specific disciplines that have common interests for the specific subissue. At the rightmost column section numbers for the issues and subissues are listed. These section numbers refer the reader to more detailed text descriptions of the design tradeoffs that follow Table 2. Each text section is structured so that it may be read independent of other sections. If text sections are read linearly, a certain amount of redundancy should be expected.

Table 2. Tradeoff Issues and Sub-Issues with respect to Discipline Perspective.

| Tradeoff | Discipline Perspective | | | | | | Ref. |
|---|---|---|---|---|---|---|---|
| ISSUE Sub-issue | Hardware | Software | Human Factors | Management | Marketing / Users | System / Safety | Section # |
| DISPLAY HARDWARE CATEGORY | | | | | | | |
| TYPE | | | | | | | I |
| Display Size / Readability | | | | | | | I.a |
| Display Resolution / Readability | | | | | | | I.b |
| Fit / Size | | | | | | | I.c |
| Retail Cost | | | | | | | I.d |
| Display Resolution / Program Complexity | | | | | | | I.e |
| COLOR / MONO-CHROME | | | | | | | II |
| Monitor Type / Update Rate | | | | | | | II.a |
| Monitor Type / Cost | | | | | | | II.b |
| Color / User Preferences | | | | | | | II.c |
| Program Complexity / Usability | | | | | | | II.d |
| Program Complexity / User Preferences | | | | | | | II.e |
| CONTROLS | | | | | | | III |
| Touch Screen / Cost | | | | | | | III.a |
| Touch Screen / Program Complexity | | | | | | | III.b |
| Touch Screen / Overheating | | | | | | | III.c |

| Tradeoff | Discipline Perspective | | | | | | Ref. |
|---|---|---|---|---|---|---|---|
| ISSUE Sub-issue | Hardware | Software | Human Factors | Management | Marketing / Users | System / Safety | Section # |
| Control Location / Usability | | | | | | | III.d |
| Control Configuration / User Preferences | | | | | | | III.e |
| DISPLAY FORMAT CATEGORY | | | | | | | |
| TRACK-UP / NORTH-UP ORIENTA-TION | | | | | | | IV |
| Program Complexity / Cost & Schedule | | | | | | | IV.a |
| Program Complexity / User Preferences | | | | | | | IV.b |
| MENUS | | | | | | | V |
| Program Complexity / Workload / Simple Interface Preference | | | | | | | V.a |
| Program Complexity / Cost | | | | | | | V.b |
| VARIABLE ZOOM | | | | | | | VI |
| CPU Speed | | | | | | | VI.a |
| Amount / Type of Information Stored | | | | | | | VI.b |
| Data Storage Type / Retrieval Mechanisms/ Cost | | | | | | | VI.c |

| Tradeoff | Discipline Perspective | | | | | | Ref. |
|---|---|---|---|---|---|---|---|
| ISSUE Sub-issue | Hardware | Software | Human Factors | Management | Marketing / Users | System / Safety | Section # |
| Data Storage Type / Retrieval Mechanisms/ Fit | | | | | | | VI.d |
| Program Complexity / Filtering Information / Cost | | | | | | | VI.e |
| Workload Requirements / Display Resolution / Information Displayed | | | | | | | VI.f |
| Information Overload / Program Complexity | | | | | | | VI.g |
| VISUAL VS. AUDITORY | | | | | | | VII |
| Visual Display Type / Program Complexity | | | | | | | VII.a |
| Visual Display Type / Fit | | | | | | | VII.b |
| Speech Generator Type / Program Complexity | | | | | | | VII.c |
| Speech Synthesizer / Heat Limitations | | | | | | | VII.d |
| Program Complexity / Cost | | | | | | | VII.e |

| Tradeoff | Discipline Perspective | | | | | | Ref. |
|---|---|---|---|---|---|---|---|
| ISSUE Sub-issue | Hardware | Software | Human Factors | Management | Marketing / Users | System / Safety | Section # |
| Cost / Distraction / Auditory Display Preference | | | | | | | VII.f |
| Distractions / Understand-ability | | | | | | | VII.g |
| NAVIGATION SYSTEM CATEGORY | | | | | | | |
| GPS vs. INS | | | | | | | VIII |
| Position Information Accuracy | | | | | | | VIII.a |
| Error Checking Capabilities / Cost | | | | | | | VIII.b |
| GPS / Cost | | | | | | | VIII.c |
| System Weight | | | | | | | VIII.d |
| Aesthetics / Receiver & Antennae | | | | | | | VIII.e |
| CONTEXT CATEGORY | | | | | | | |
| WEATHER | | | | | | | IX |
| Interference-Data Reception Problems / Mental Workload Issues | | | | | | | IX.a |
| Interference-Data Reception Problems / High Temperatures / Corrosion | | | | | | | IX.b |
| SAFETY | | | | | | | X |

| Tradeoff | Discipline Perspective | | | | | | Ref. |
|---|---|---|---|---|---|---|---|
| ISSUE Sub-issue | Hardware | Software | Human Factors | Management | Marketing / Users | System / Safety | Section # |
| Software Glitches / Traffic Accidents / Lawsuits | | | | | | | X.a |
| Design Errors leading to Human Error / Traffic Accidents / Lawsuits | | | | | | | X.b |
| GLARE | | | | | | | XI |
| Curve, Type of Display / Readability | | | | | | | XI.a |
| Display Tilt / Cost / Non-glare Screen | | | | | | | XI.b |
| TRAFFIC | | | | | | | XII |
| Cost / Traffic Updates Information | | | | | | | XII.a |

*Display Hardware.* The experts identified several issues concerning the display hardware. This is hardware primarily used for displaying information to the driver. This area focused mostly on technical constraints of the design.

I. Display Type. The experts identified several issues with respect to the display type used. Display type refers to the actual physical monitor type to be used to display the moving navigation map.

a. The display size may affect the readability of text and images. The larger the size of the display, the more readable it would be. The Human Factors Expert would want a larger display. The Hardware Expert, however, would have considerable say into the display size used.

b. Display resolution affects the readability of characters on the display surface. If resolution is low, readability would be negatively affected. Thus, the Human Factors Expert would be concerned with resolution and its impact on readability. In addition, the Software Expert would need to consider the display resolution limitations when developing software for the display.

c. Display type, power supply type, and cooling equipment type are major concerns when considering electrical and system compatibility. Electrical compatibility of the navigation unit must be considered with respect to the vehicle's current electrical systems. Also, physical fit of the display, power supply, and cooling equipment must be considered and planned for. These would be issues for the System / Safety Expert. Also, integration of these subsystem components must be considered with respect to the navigation system in isolation and would be handled by the Hardware Expert.

d. Retail cost of the navigation unit is partially based on a combination of the project costs and an expectation of what the end user is willing to pay for the system. Increases in project cost, would lead to increases in retail cost. The project cost must be balanced against the projected amount the end user is willing to pay for the system. The Management Expert would be responsible for keeping the project costs to a minimum while the Marketing / User Expert would be responsible for determining a fair price (partially based on the willingness factor) for the system and its installation.

e. Display type partially determines the level of display resolution. Various display types offer differing levels of resolution. The display type decision would primarily be made by the Hardware Expert. The Software Expert, however, must know the resolution of the selected display to develop appropriate software.

II. *Color Versus Monochrome Screen.* The experts identified two options for monitor screen type that would affect color. The two options were either a color screen or a monochrome screen. Screen choice would most likely be limited to either LCD (Liquid Crystal Display) or CRT (Cathode Ray Display) type monitors. CRT monitors have greater color capabilities than LCD monitors.

a. The update rate, or screen refresh rate, of the monitor is important to consider in developing this system. CRTs have slower update rates than LCDs. The decision concerning monitor type would primarily be the responsibility of the Hardware Expert. The Software Expert must take into consideration update rates of specific monitors when developing software for the system.

b. Project cost is affected by the color level wanted in the monitor. The more colors that the monitor must support, the more expensive the monitor would be. This added expense would be

added into project costs. CRTs can generate more colors and would be less expensive than LCDs. Thus, project costs would increase if LCDs were chosen. Decisions concerning monitor type would primarily be made by the Hardware Expert. Any decision that increases project costs would concern the Management Expert.

c. In general, end users prefer color in their displays. Thus, a color monitor has greater utility from the perspective of the Marketing/User Expert. The decision concerning the type of monitor, however, resides primarily with the Hardware Expert.

d. Using many colors in a display would increase the program complexity, but tends to aid in the readability of text and identification of objects. In turn, this leads to reduced mental workload for the operator which would concern the Human Factors Expert. The Software Expert, however, would be concerned with the increased software complexity that results from supporting many colors.

e. An increase in software complexity would result if many colors were used in the display. Use of color in the display would be preferred by the Marketing /User Expert due to user preferences for color. Because color is associated with increased program complexity, the Software Expert may be at odds with this preference.

III. *Control Issues*. The experts identified several issues concerning system control issues. Control issues deal with how the operator inputs commands into the system.

a. Touch screen control inputs could be used in the system, but would increase project cost. The decision to use a touch screen would be made primarily by the Hardware Expert. Any increase in cost associated with the installation of a touch screen would also concern the Management Expert.

b. The complexity of the programming would increase if a touch screen control input were used in the system. Although a touch screen might be a desirable option for the Hardware Expert, the Software Expert must write software to fit the control device. Thus, the Hardware Expert and the Software Expert may be at odds.

c. A touch screen may become too hot to touch during normal operation of the navigation system. Thus, desirability of the touch screen from the Hardware Expert's perspective must be considered with respect to the System / Safety Expert's concerns for developing a safe and hazard free system.

d. Display access, distraction issues, and reach / anthropometry issues are affected by the location of control inputs with respect to the driver. Poor location of control surfaces can lead to difficulty in viewing the display, distraction away from the primary task of driving the vehicle, and awkward control of the display. The Human Factors Expert would be concerned primarily with these issues, as would the System / Safety Expert due to their impact on driver safety.

e. The development of user friendly control configurations that are appealing to customers must be balanced against issues concerning display access, distraction, and reach / anthropometry concerns. Sometimes these factors may be at odds. A configuration that is accessible, offers reduced distraction, and has adequate reachability may not be appealing or intuitive enough for the user to operate. The Marketing / User Expert would be concerned with the attractiveness of the control configuration to the user, while the Human Factors Expert would be concerned with its usability.

*Display Format.* The experts identified several issues concerning the display format used to present information to the driver.

IV. <u>*Track-Up Versus North-Up Map Orientation*</u>. The experts identified two options for map orientation. The first option was a track-up orientation. In a track-up orientation, the car icon on the display is always oriented in the direction of travel. Therefore, the map must rotate around the car to keep constant orientation. The second option was a north-up orientation. In a north-up orientation, the map remains in a constant orientation and the car icon would rotate with respect to the direction traveled.

a. Selection of display format can affect the level of program complexity required to present the format. The greater the complexity, the more time required to write the software and the higher the project costs. Both track-up and north-up format orientations have unique attributes that would require special software. Increasing the project cost and schedule would be an issue for the Management Expert, while the Software Expert would be more concerned with the programming complexity.

b. Imaging generation techniques used to present graphics require varying levels of programming complexity. Raster / bitmap techniques would be preferable from a Marketing / User perspective because they generate more realistic graphics. From the Software Expert's perspective, however, raster / bitmap techniques are harder to implement than other techniques (e.g., vector drawing).

V. <u>*Menus*</u>. The experts identified several issues with respect to the menu structure to be used. Menu issues are concerned with the organization and hierarchical ordering of commands and the users' ability to access and input necessary information using the navigation system's interface.

a. A "simple" interface has a command structure that is straightforward, is not distracting, and has relatively few control inputs. "Simple" menuing interfaces involve greater complexity because of "behind the scenes" programming to simplify user control inputs. The Human Factors Expert and Marketing / User Expert strongly prefer a "simple" interface. Increased program complexity, however, would concern Software Experts because they must write the software.

b. Increasing the level of program complexity would increase project costs and extend the project timeline. Increased complexity of the software may result if a "simple" interface is wanted. The Management Expert would be concerned with increases in project cost and schedule, while the Software expert would be concerned with the effects of increasing program complexity.

VI. <u>*Variable Zoom Issues*</u>. The experts identified several issues concerning the use of variable zoom. These issues dealt with the relative advantages and disadvantages of giving the user the option to zoom in on particular location details. Using a variable zoom option assumes the decision to incorporate a visual display into the system.

a. In designing software, the processor speed limitations must be considered when attempting to implement zoom features. The zoom features may be limited by the CPU speed. The Hardware Expert would be the most knowledgeable about the CPU and would interact with the Software Expert to create the required software needed for zoom features.

b. The amount and type of information needed for zoom features would dictate the type of database and the complexity of the retrieval / storage mechanisms required. The more complex the

database, the more expensive it would be. This added cost would most likely be absorbed into the system's retail cost. This would concern Marketing / User Experts since they want to keep the system cost affordable for the end users. The choice of database and retrieval / storage mechanisms would most likely fall to the Hardware Expert.

c. The more detailed the level of information needed for zoom features, the more monetary cost that would be incurred in gathering the necessary information. Also, a more complex database and retrieval / storage mechanism would be required. This would increase project costs, because the database would be more expensive. The Management Expert would be concerned with the cost of the required database and the cost accrued in information gathering activities. The choice of database and associated retrieval / storage mechanisms would likely be made by the Hardware Expert.

d. The data storage device type would be constrained by the physical fit of the device into the vehicle itself. Various drive types are shaped differently and have different options for mounting and placement within the vehicle. This physical fit issue would require input from the System / Safety Expert. The System / Safety Expert would likely consult the Hardware Expert because the data storage device would be a Hardware issue.

e. Filtering of information may be required to reduce the presentation of irrelevant information to the driver. The filtering algorithm / mechanism would likely increase the software complexity. In addition, filtering of raster / bitmap images may prove to be quite difficult to accomplish with software. Dealing with these issues would increase project costs. The Software Expert would need to develop filtering methods that filter information correctly and efficiently. The Management Expert, however, would be concerned with any related additions to project cost.

f. Auto-decluttering would be a useful feature in the navigational system to reduce screen clutter when presenting traffic congested areas. Cluttered displays caused by presentation of traffic congestion would increase the driver's mental workload. Mental workload would also increase if screen resolution was low. The screen may be more difficult to interpret because images may be less well defined. The Human Factors Expert would want a high resolution screen and an auto-decluttering mechanism built into the system so that driver mental workload would be reduced. The Hardware Expert, however, would ultimately determine the screen resolution to be used.

g. If the driver is presented with too much information, information overload may occur. Preventing this would require a complex auto-decluttering software solution. The Human Factors Expert would probably want this type of feature to decrease the chances of information overload, but the Software Expert would be concerned with its incorporation into the system because it adds program complexity.

VII. *Visual Versus Auditory Displays*. The experts identified two format options for how information might be displayed to the operator. The first option was to use a visual display. In this method, all information would be presented via a visual display surface. The second option was to use an auditory display. Information would be presented to the driver aurally using speakers placed in the vehicle.

a. The visual display type would affect the software complexity required to operate the display. As the complexity of the display increases, the complexity of the software increases. The decision to select the visual display type would likely fall to the Hardware Expert, while the Software Expert would deal with any added programming complexity.

b. Given a specific visual display, the physical fit of the display unit and associated hardware must be considered with respect to the current vehicle configuration. In other words, the display unit, cabling, and other necessary hardware must fit into the vehicle. The System / Safety Expert would need to deal with this issue and would likely consult with the Hardware Expert on the required display hardware needed to be placed within the vehicle.

c. If an auditory display were used in the system, additional software for use with a speech generator would need to be created. The program needed to operate a speech generator may be quite complex. Generally, the more complex the generator, the more complex the software that would be required. Thus, the Software Expert would be concerned with the software required and the Hardware Expert would be concerned with the specific speech generator that would be used.

d. Overheating of the speech generator, both internal and external, can adversely affect the understandability of the speech produced. If understandability is poor due to heat effects, the driver may be attending too closely to the voice and be distracted from the primary task of driving. This distraction issue would concern the Human Factors Expert and the System / Safety Expert. In deciding which speech generator to use, the Hardware Expert would need to consider the heat limitations of the speech synthesizer used in the generator.

e. Using an auditory display would require more complex software than a visual display. The production of sound generation software would require more resources and would increase the overall project cost. The Software Expert would be concerned with how to create the software needed, while the Management Expert would be concerned with how it would impact project cost.

f. Auditory displays would be desirable because they can serve as aural reminders of approaching turns and directions the driver must take. These aural reminders, however, may be distracting if the driver has difficulty understanding and comprehending the sound. In addition, use of an auditory display would increase project costs. The Human Factors Expert would be concerned with any resulting distractions, while the Management Expert would be concerned with increased costs.

g. Poor understandability of the synthesized voice can be a concern for two reasons. First, if voice understandability is poor, the system may not be usable. Second, poor understandability may distract operators from the task of driving because they spend time trying to comprehend the voice. Poor usability would likely result in low consumer sales which would be an issue for the Marketing/User Expert. The issue of distraction would concern the Human Factors Expert.

*Navigation Systems.* The experts identified several common areas of concern with the Navigation System. The Navigation System is composed of the primary devices used in plotting, tracking, and directing the path of the vehicle.

VIII. <u>*GPS vs. INS*</u>. In general, there are two types of navigation devices to be considered. The first type was an Inertial Navigation System, or INS. In this type of system, the location and direction of the vehicle are determined by an internal compass and motion sensors. The second type of system was the Global Positioning System, or GPS. This type of system relies on information relayed from satellites to determine longitude and latitude. The position is then plotted on a map stored in the database. The GPS system requires the use of a receiver and antennae on the vehicle.

a. In a GPS system, incoming location data must be plotted by the navigation system against the internal map database. Inaccuracies / incongruencies, however, may occur between

position and map database data. This may lead to traffic accidents and other safety issues for the System / Safety Expert. The Hardware Expert would be concerned with how the system plots and what mechanisms would be used.

b. Error checking capabilities may be needed to deal with the inaccuracies and incongruencies caused by difficulties in matching location and map database information. This capability would involve more complex software, leading to increases in the project's cost. Project cost would be an issue for the Management Expert, while the Software Expert would be concerned with the implementation of proper program mechanisms to check for errors.

c. The cost of the various types of navigation systems must be considered when deciding upon a specific one to implement. For example, GPS systems are more expensive than INS systems. On the other hand, GPS systems are also more desirable because of their better accuracy. The decision about which system to implement would likely reside with the Hardware Expert. Because cost would be an issue, the Management Expert would also have some input.

d. Weight differences between navigation systems must be considered with respect to the total system weight added to the vehicle. An INS system would weigh more than a GPS system. Consideration of weight would concern System / Safety Experts. They would need to interact with the Hardware Expert, who has primary responsibility for choosing a navigation system.

e. It is important to consider system aesthetics (i.e., consumer appeal) of a selected navigation system to avoid potential negative effects on final sales. If a system is externally unattractive, consumer reactions may be negative and result in poor sales. For example, the antennae and receiver components of a GPS system must be mounted to the vehicle's exterior. This may cause the vehicle to look aesthetically unappealing. This issue of consumer appeal would be an issue for the Marketing / User Expert. The Hardware Expert would be concerned with the types of external equipment to be mounted to the vehicle.

*Context.* The experts identified several context issues that would affect how the system operates. The context issues deal with external or environmental variables the system must be able to cope with. These issues include weather, glare, traffic, and safety.

IX. *Weather Issues*. The experts identified several issues with respect to weather and its impact on the entire system.

a. An increase in mental workload may result if software is inadequate at correcting poor information due to bad weather interference. This may increase the difficulty experienced by the operator in interpreting the information correctly. The difficulty may lead to an increase in mental workload which would concern the Human Factors Expert. The level, or quality, of weather corrections would be dependent on the ability of the software to transparently correct errors. This would concern the Software Expert.

b. Reception of traffic information could be affected by physical damage caused by corrosion and weather. This could adversely affect the quality of reception and increase the mental workload of the driver if provisions are not made to correct for these problems. The impact of these factors on the physical systems would concern the Hardware Expert, and the System / Safety Expert would be concerned about how they affect driver safety. Additional workload caused by trying to interpret the system may distract the operator while driving the vehicle.

X. *Safety Issues*. The experts identified several issues with respect to the overall safety of the system.

a. Inaccurate or incorrect information presented by the system due to software bugs and errors may lead to traffic accidents. The Management Expert and Marketing/User Expert would be concerned since lawsuits may be brought against the manufacturers if the fault lies with the system. The Software Expert would be concerned with attempting to correct any bugs with the program.

b. Design errors in the system may lead to human errors while driving. This can be potentially disastrous because this could lead to traffic accidents. The Human Factors Expert would be concerned with human error caused by design errors. Management and Marketing/User Experts would be concerned with design errors because any resulting traffic accidents could lead to lawsuits.

XI. *Glare Issues*. The experts identified several issues concerning screen glare.

a. If glare is present, the operator may find it difficult to read the display. This may increase the mental workload of the operator. Glare would be affected by type of monitor and curve of display surface. The issue of readability would concern the Human Factors Expert. The Hardware Expert would probably choose the type of monitor / display curvature and may need to consider the opinions of the Human Factors Expert.

b. Improper display tilt can cause glare and reduce the readability of the display surface. A non-glare screen could be installed to prevent these problems, but this would increase project costs. The Hardware Expert and the Human Factors Expert share the same concerns about glare and its effects on readability. Both Experts' would want a non-glare screen installed in the system. The Management Expert, however, would be concerned with any increased costs. The System / Safety Expert would be concerned with the danger of glare interfering with normal vision or blinding the operator during driving.

XII. *Traffic Issues*. The experts identified a single issue of common concern focused on traffic issues. This concern was shared by the Management and the Marketing/User Experts.

a. The cost of transmitting and receiving constant traffic updates to and from the vehicle would be expensive. However, having constant traffic updates would be more appealing to customers and would be wanted by the Marketing/User Expert. The Management Expert would be concerned with the added cost of having this feature and its effect on overall project costs.

## DESCRIPTION OF THE EXPERIMENTAL TASK: AUTOMATE

After examining the information provided by the experts, we narrowed the design problem down to the issue of designing an auditory display for the automobile navigation system. The relevant tradeoffs were drawn from the information provided by the experts. The task was designed to study the critical collaborative issues of information sharing and misanalogies. Stasser's (Stasser & Titus, 1985; 1987) hidden profile paradigm was modified for this purpose. In the hidden profile paradigm, decision makers are given information about three candidates (e.g., job candidates). Some of the information is shared among all of the decision makers. Unique information is given to individual decision makers. The shared information favors one candidate, while the combination of shared and unique information favors a different candidate. Thus, the hidden profile can only be discovered and the correct decision made if the group discusses all of the information (both unique and shared). If the group's discussion focuses on only shared information, the group is likely to arrive at the wrong decision.

This paradigm was modified for multidisciplinary design teams by focusing on decision alternatives for the auditory display of the navigation system. The decision alternatives were three different sound boards that could be used to produce the speech required for the audio display. Appendix A shows the sound board options. This information will be shared among all design team members. In addition, information about the design specifications (See Appendix B) and speech synthesis options (See Appendix C) will be shared with all design team members.

Decision makers will be given unique or unshared information that is relevant to their particular design background. Information for three design backgrounds are provided in Appendices D, E, and F. For example, information for a Human Factors Expert is presented in Appendix D. This information focuses on the primary concerns of driver information processing load and speech intelligibility. Appendix E presents the information for a Computer Engineer. This information focuses on the primary concerns of data storage and power consumption. Appendix F presents the information for a System / Safety Engineer and focuses on the issues of quality and fit.

Embedded in the unique information are critical pieces of knowledge. If the design team's discussion focuses on only shared information, the best design candidate of the speech processing boards would be the Voice Player because of its low cost. It can produce CD quality sound, appears to be able to withstand the air temperatures specified in the design specifications, and includes the text-to-speech program. But, critical pieces of the unshared information make this board less desirable: 1) the board must withstand temperatures found within an automobile which are more extreme than air temperatures (See Computer Engineer's information in Appendix E) and 2) because this board has no compression capabilities it would add to the data storage requirements increasing the costs (See the Computer Engineer's information in Appendix E and the System / Safety Engineer's information in Appendix F).

The unshared information combined with the shared information indicate that the Orator would be the best selection. For the team to realize this they must overcome a potential misanalogy concerning the sampling rate. The shared information states that the best sampling rate is 44.1 kHz and that this is equivalent to CD quality sound. The misanalogy occurs because quality music recordings require higher sampling frequencies than quality speech recordings. The Human Factors information (Appendix D) clearly indicates that sampling frequencies of 22 kHz produce high quality speech recordings and that sampling frequencies above 22 kHz do not add to the quality.

In addition, a potential conflict between the Human Factors Expert and the Computer Engineer needs to be resolved to achieve the most efficient system. This conflict focuses on the type of speech synthesis that will be used. Due to speech intelligibility requirements, the Human Factors Expert is likely to favor using digitized synthesis. The Computer Engineer, however, is likely to want text-to-speech due to its reduced data storage requirements. The two competing viewpoints can best be satisfied by a compromise. The compromise involves using text-to-speech for all words that are pronounced according to common pronunciation rules. But, exceptions can be stored digitally. This option requires only 1/3 of the data storage for digitized words and maintains high levels of speech intelligibility.

## POTENTIAL APPLICATIONS FOR AUTOMATE

Many potential research questions could be addressed using this paradigm. Three of these questions are discussed as illustrations. First, design teams communicating over a computer can be compared with those communicating face-to-face. Since computer-mediated communication (CMC) involves a narrower bandwidth than face-to-face (FTF) communication (Wellens, 1986; 1989), some information communicated by computer may be lost (e.g., nonverbals) or distorted. Communication across computers may actually hinder the effectiveness of design teams. On the other hand, CMC may diminish pressures for team members to conform and reduce barriers to social interaction resulting in more equal participation than FTF (Kiesler, Siegel, & McGuire, 1984). Thus, it would be interesting to use the AutoMate paradigm to explore whether design teams using CMC actually discuss more unshared information than FTF design teams.

Second, the paradigm can be used to study how teams with members located in two different locations work together. If multidisciplinary design teams are physically dispersed, individuals from functionally similar domains may be located near each other and likely to form coalitions or subgroups. These coalitions may change the dynamics of the communication process because teams tend to be more competitive than individuals. AutoMate can be used to study how coalitions in design teams might influence information sharing.

Third, the paradigm can be used to study how design tools such as automated databases or design rationale databases influence team decisions. In addition, AutoMate may be used to examine the impact computerized design demonstrations or rapid design prototyping software have on a team's development of a shared perspective. For example, the Computer Aided Systems Human Engineering (CASHE) software system (see Boff, Monk, Swierenga, Brown, & Cody, 1991) includes a (1) comprehensive human factors engineering database and (2) human perception and performance prototypers which could be used to amplify the human factors perspective in the Automate task. The influence of these types of computer design tools on information sharing and team decision making would also be interesting to examine.

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Appendix A

## Sound Board Options

| | Voice Player VOP645 | Orator OR987 | Sound Creator SC555 |
|---|---|---|---|
| Sampling Rate | 4 to 44.1 kHz programmable | 4 to 22 kHz programmable | 4 to 44.1 KHz programmable |
| Operation Temperature | $-55^0$ to $140^0$ F | $-55^0$ to $185^0$ F | $-55^0$ to $185^0$ F |
| Text-to-Speech Program | Program included on board | Program included on board | Available at an additional cost of $5.00 per unit. |
| Maximum Current | 10mA | 10mA | 4mA |
| Data Compression and Decompression | None | 4:1 | 4:1 |
| Price per unit | $50.00 | $60.00 | $65.00 |

Appendix B

## Design Specifications For The Automate Audio Display

### Cost

- Target cost is $75 per unit
- Cost maximizing profit is $60 or less
- Cost at which system becomes less feasible is $100 or more

### Features

- Messages giving brief instructions about the next driving maneuver (e.g., lane change, turn, exit) required.
- Messages providing driver with information about present location and direction heading

### Criteria

- High quality sound is preferable. High quality sound depends on the rate at which sound is sampled. The higher the sampling rate the better the sound quality. For example, Compact Disc (CDs) quality sound is sampled at a rate of 44.1 kHz.
- The system must withstand car temperatures that vary with weather. The range of air temperatures in the targeted markets varies from $-20^0$ F to $110^0$ F
- Data storage for messages must be under 70 Mb or the cost of additional memory for data storage must be included in cost estimates.
- Overall cost of the system

### Action Decision Items

- Which sound board should be used? ____________________
- What type of speech synthesis will be used: text-to-speech or digitized?

  ____________________
- What is the estimated total cost of the audio display?

Sound Board ____________________
Speech Synthesis ____________________
Additional Memory ____________________
Total Cost ____________________

Appendix C

## Speech Synthesis Options

Two basic options exist for generating and storing messages for AutoMate's auditory display: digitized or text-to-speech. These options can be used separately or in combination.

### Digitized

- Messages are converted into a format that a computer can understand and stored on the hard drive of the computer.
- The conversion involves sampling sound at a certain frequency. The quality of the sound will depend on the frequency it is sampled at. Crisper clearer sound is produced at high frequency rates. Higher sampling rates, however, require more storage.
- Storage requirements are dependent on the sampling rate and data compression. But, can quickly exceed storage capacity.

### Text-to-Speech

- Messages are generated from text based on basic rules of pronunciation. A set of algorithms is used to break down a written word into its basic speech components.
- Only a small set of sounds need to be stored to produce an unlimited vocabulary.
- Recent advances in text-to-speech synthesis have produced high quality speech for most words that follow the basic rules of pronunciation. Exceptions still pose a problem. About 1/3 of all street names do not follow typical pronunciation rules.

Appendix D

# Human Factors Information

## Focus

- Usability

## Primary Concerns

- Burden on Driver's Information Processing Demands
  - Distraction--Users should not be distracted from their primary task of driving.
  - Memory Load--Users' ability to remember information should not be taxed.
- Intelligibility
  - Identifiability--Users should be able to correctly identify words that are used in messages.
  - Quick and Easy Recognition--Users should be able to recognize words quickly without having to decipher them.

## Issues

- Digitized messages are more intelligible when sampled at a higher frequency.
  - Under optimum conditions (i.e., low noise, low distractions, etc.) a message with a frequency range of 200 to 6100 Hz will be about 95 percent intelligible. Reducing this rate will produce a decrease in intelligibility, particularly of consonant sounds such as "th" which are composed largely of higher frequencies.
  - A good rule of thumb to follow is that sound should be sampled at about 3 times the highest sound frequency that you are interested in. The intelligibility of speech increases up to about the 22 kHz sampling frequency and then levels off. This means that higher sampling frequencies do not have a significant impact on intelligibility.
- The intelligibility of digitized and text-to-speech generated messages is about the same for most words.
  - For exceptions, digitized messages are more intelligible. Exceptions will add to the operators mental workload and burden processing demands.

Appendix E

# Computer Engineer Information

## Focus

- Performance of the audio display given computer hardware and software constraints

## Primary Concerns

- Program and Data Storage Requirements
  - Hard disk space available is 70MB
  - Data storage depends on the type of speech synthesis, the rate that the sound is sampled at, and the amount of data compression available.
- Power consumption limitations
  - Under normal operating conditions the speech processing board can draw no more than 50mA of current.

## Issues

- Information stored at higher sampling frequencies require more space.
  - Information stored at 22 kHz takes half the space that information stored at 44.1 kHz takes. Compressed data takes 1/4 of the space that uncompressed data does. Below is a table estimating the storage requirements

| | Sampling | Rate |
|---|---|---|
| | 22 kHz | 44.1 kHz |
| All street names digitized and stored | | |
| With Compression (4:1) | 180 MB | 360 MB |
| Without Compression | 720 MB | 1.5 GB |
| All street names generated text-to-speech | | |
| With Compression (4:1) | 10 MB | 20 MB |
| Without Compression | 40 MB | 80 MB |

Appendix F

## System/Safety Engineer Information

### Focus

- Quality of the auditory display and overall fit within the system

### Primary Concerns

- Quality
  - Reliability of performance--The auditory display must operate consistently without software or hardware bugs.
  - Must meet all constraints from the environment--The display must operate under extreme weather conditions that might affect automobiles.
- Fit
  - The sound boards must fit within the selected computer system
  - Data storage requirements beyond 70 MB require an upgrade to the hard drive of the computer used for the navigation system.

### Issues

- All three boards have been tested and work equally well. Quality of the three is considered comparable.
- Overheating of the sound boards could be problematic. Due to the greenhouse effect within an automobile, temperatures usually range from $-35^0$ to $165^0$ F
- All three boards fit within the overall AutoMate system
- The cost of additional data storage is estimated in the table below.

Cost of Additional Data Storage

| Cost | 70 MB | 200 MB | 360 MB | 720 MB | 1 GB | 2 GB |
|---|---|---|---|---|---|---|
| Per Unit | $ 0 | $ 50 | $ 75 | $130 | $300 | $600 |

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